The Performance of a Heat Sink

with Piezoelectric Fins

An LED light is often made of a small piece of semiconductor, an integrated optical lens used to shape its radiation pattern, and a heat sink, used to dissipate heat and maintain the semiconductor at a low operating temperature. LED lights present many advantages over incandescent light sources, including lower energy consumption, longer lifetime, improved physical robustness, smaller size and faster switching. LED lights are powerful enough for room and street lighting and are relatively expensive. They also require more precise current and heat management than traditional incandescent and compact fluorescent lamp sources of comparable output.

The performance and life expectation of an LED light directly links to the semiconductor temperature, so-called “junction temperature”. Generally, the lower the junction temperature is, the better the performance and the longer the life of the LEDs. To increase the durability and the lighting quality of the LEDs, thermal management is a critical aspect of the design. For indoor lighting applications, using a mechanical fan/blower to cool the LED is out of question, due to acoustic noise and reliability concerns. So, most LED lights used in homes are cooled with heat sinks by natural convection (see Figure 1). However, for high power LEDs, this passive thermal solution will reach its performance limit due to low convective heat transfer coefficient, space limitations and weight restriction. Some engineers have introduced piezoelectric fans and synthetic air jets into LED light cooling to enhance the convection heat transfer. Other researchers, Ma et al. [1], proposed the use of heat sinks with piezoelectric fins. This paper discusses this novel concept of cooling LED heat sinks.

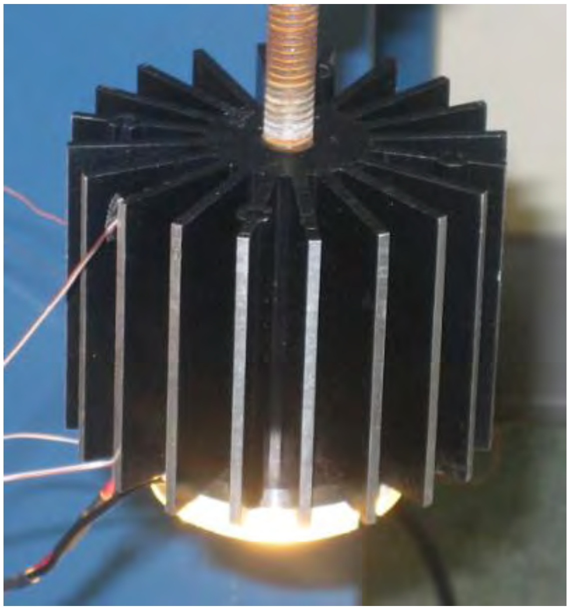

Figure 1. STAR LED Heat Sink (courtesy of Advanced Thermal Solutions, Inc.)

The piezoelectric effect is the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials. The piezoelectric effect is a reversible process, in that materials exhibiting the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electrical field). A piezoelectric fin is constructed by using the reverse piezoelectric effect. Ma et al. proposed to apply piezoelectric materials on a copper fin, see Figure 2.

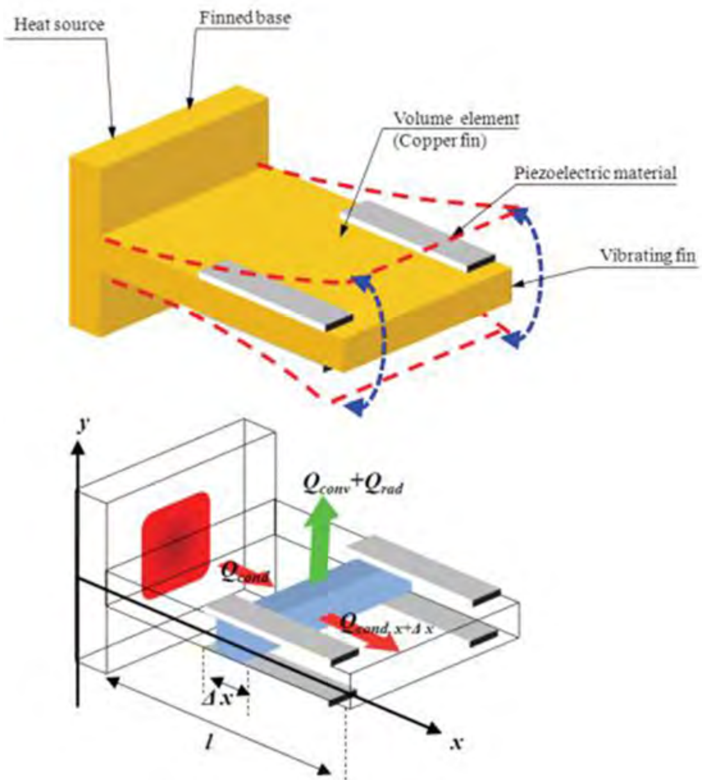

Figure 2. The Structure of a Piezoelectric Fin [1]

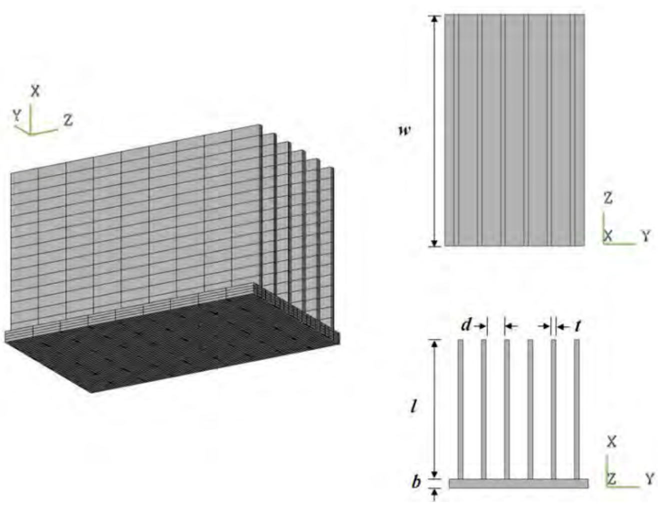

Figure 3. A 3D Transitional Model of a Heat Sink with Six Piezoelectric Fins [1]

When alternative voltage with certain frequency is applied on the piezoelectric materials, they vibrate and cause a vibrating motion of the copper fin. The vibrating motion of the fin will enhance the convection heat transfer coefficient from the fins by creating enhanced air flow between fins.

To parametrically investigate the performance of the heat sink with vibrating piezoelectric fins, Ma et al. [1] built a 3D transitional model of a heat sink with six (6) piezoelectric fins in CFD-GEOM software (see Figure 3). In the model, Ma et al defined the l as fin length, w as fin width, d as fin pitch, b as base thickness, and t as fin thickness.

By solving the CFD model, they studied the piezoelectric fin heat sink performance and compared it with a traditional straight fin heat sink. In their simulation, the ambient temperature is 300 K and the heat sink base temperature is fixed at 340 K.

Ma et al. [1] define the effectiveness ε of the vibrating fins as,

$$\varepsilon = \frac{Q}{Q_0}$$

Where Q the heat flux per unit area for heat a sink with is piezoelectric fins and Q_0 is the heat flux per unit area for traditional heat sink.

The displacement ratio of the fin tip D of piezoelectric fins is defined as,

$$D = \frac{a}{d/2}$$

Where a is the amplitude of fin tip motion and d is the fin pitch.

The vibrating motion of the fins is described as an equation of sine wave,

$$y = a\left(\frac{x}{l}\right)^2 \sin(2\pi f t)$$

Where l is the fin length and f is fin vibrating frequency.

To compare the effectiveness of natural convection caused by buoyance force and forced convection induced by fin vibration, Ma et al. [1] introduced a non-dimensional parameter γ,

$$\gamma = \frac{Gr}{Re_L^2}$$

Where Gr is the Grashof number, Re_L is the Reynolds number, and L is characteristic length of fin for natural convection.

Ma et al. [1] first looked at the effect of fin length, and the results are shown in Figure 4. In these cases, gravity is perpendicular to the heat sink base. For D=0.75, the piezoelectric fin heat sink underperforms traditional heat sink, if the fin length l is larger than 20 mm. For D=0.9, the piezoelectric fin heat sink outperforms traditional heat sinks consistently.

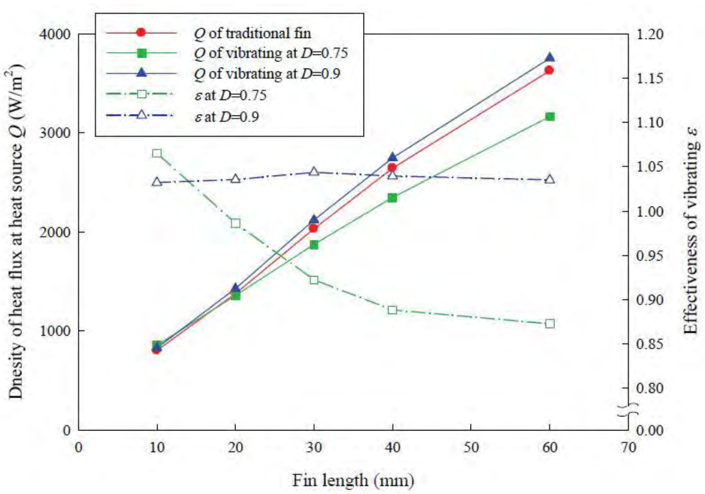

Figure 4. The Performance of Piezoelectric Fins with Different Fin Heights [1]

The effects of fin width w (see Figure 3) are illustrated in Figure 5. For both piezoelectric fin and traditional straight fin heat sinks, the heat flux dissipated by the heat sinks decreases with increased fin width. The piezoelectric fin heat sink only outperforms a traditional fin heat sink when the fin width is 100mm.

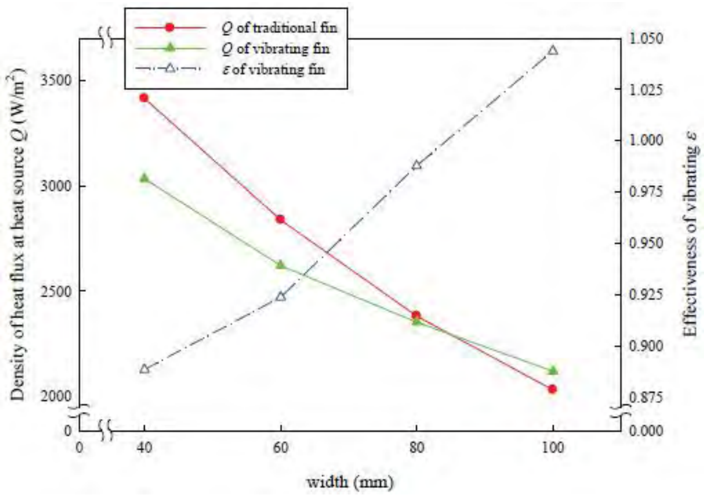

Figure 5. The Performance of Piezoelectric Fins with Different Fin Widths [1]

The effects of fin pitch d are plotted in Figure 6. The pitch between the fins influences the transition of the thermal-boundary layer. For a traditional straight fin, the optimized fin pitch is 6 mm. For vibrating fins, they can maintain a relatively stable density of heat flux in the large pitch range and obtain maximum effectiveness at a fin pitch of around 12 mm, which is about 30% better than a traditional heat sink with the same dimensions.

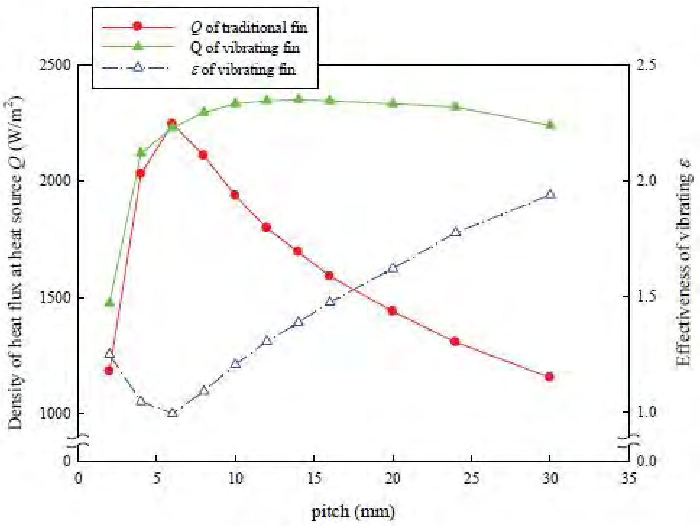

Figure 6. The Performance of Piezoelectric Fins with Different Fin Pitches [1]

Ma et al. [1] simulated two different vibrating modes for piezoelectric fin heat sinks (see Figures 7 and 8). In the Type A mode, the fins vibrate in opposite directions; in the Type B model, the fins vibrate in the same direction. They found that the Type A mode outperforms the Type B mode under the same displacement ratio, due to the breaking of the thermal boundary layer. However, the amplitude of the Type A mode is limited by the available fin pitch, which is half of the pitch. As the displacement ratio increased from 0.9 to 1.8, the Type B mode with D=1.8 can generate larger flows, resulting in greater effectiveness, as shown in Table 1.

Vibrating mode	Heat flux at heat source (W)	Density of heat flux at heat source (W/m²)	Effectiveness of vibrating
Traditional fins	4.689	3126.07	1.000
Type A (D=0.9)	5.022	3347.95	1.071
Type B (D=0.9)	4.915	3276.51	1.048
Type B (D=1.8)	5.232	3487.92	1.116

Table 1. Performance of Piezoelectric Fins at Different Vibrating Modes [1]

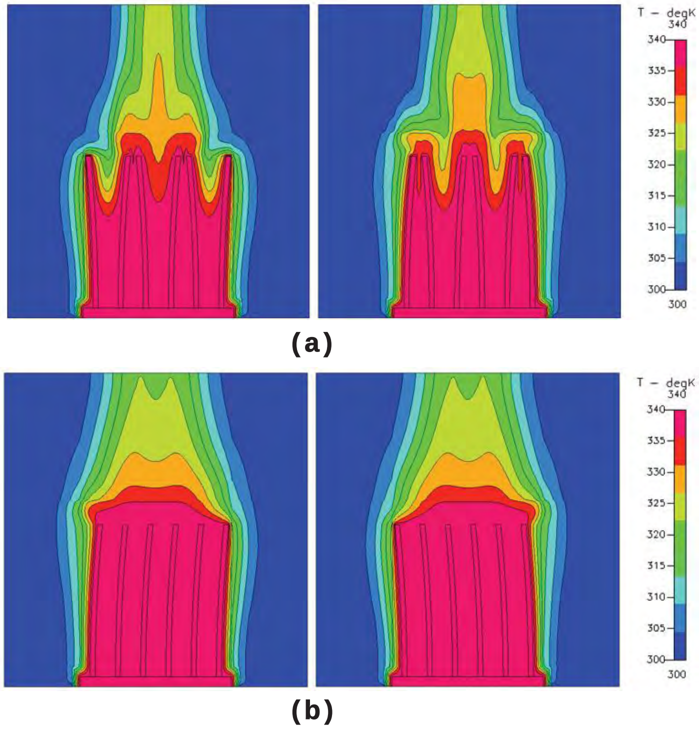

Figure 7. Temperature Distribution in a Piezoelectric Fin Heat Sink (a) Type A and (b) Type B [1]

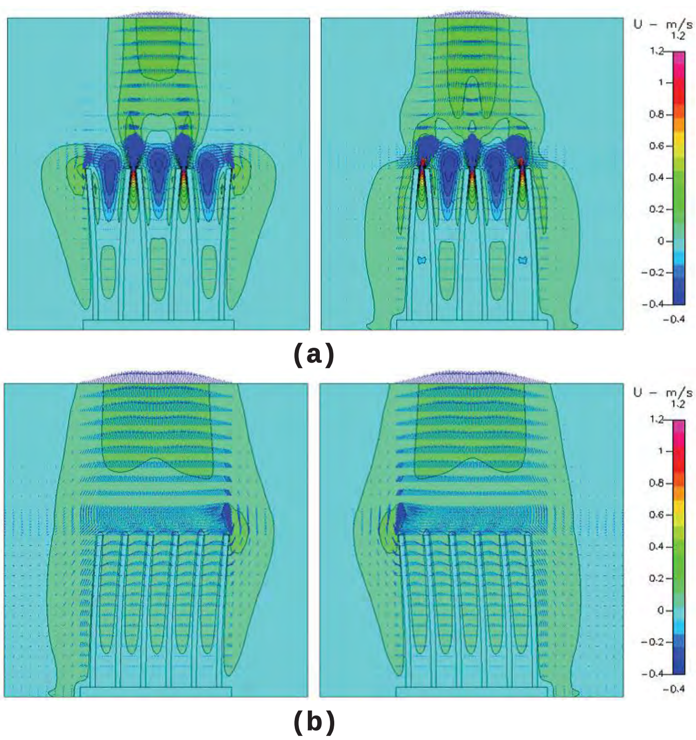

Figure 8. Velocity Distribution in a Piezoelectric Fin Heat Sink (a) Type A and (b) Type B [1]

The effects of the vibrating frequency of piezoelectric fins are illustrated in Figure 9. The piezoelectric fin heat sink effectiveness increases rapidly after 20 Hz and reaches a value of 3.8 at a frequency of 60 Hz. This shows that forced convection is the dominant factor at higher frequency. However, the human ear can hear the sound when the frequency is larger than 20 Hz. So, the potential application of running the piezoelectric fins at 60 Hz needs further investigation.

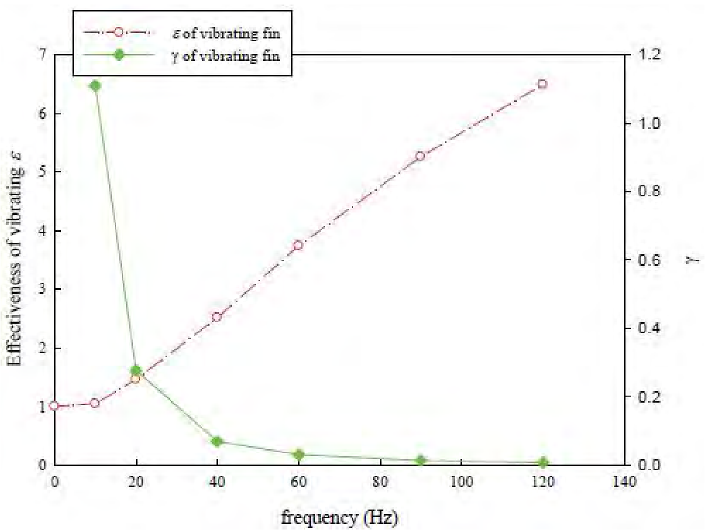

Figure 9. The Effect of Vibrating Frequency [1]

Ma et al. [1] also investigated the effect of gravity direction on piezoelectric fins. In some configurations, the buoyancy of air plays a vital role in the functioning of the piezoelectric fins. Forced convection may help or hurt natural convection heat transfer, depending on the relative direction of buoyancy-induced and forced convection motions caused by vibration. Figure 10 shows the calculated effectiveness of piezoelectric fins for different gravity directions. If the gravity is perpendicular to the heat sink base, the piezoelectric fin heat sink outperforms the traditional heat sink only when D is larger than 0.9. If the gravity is parallel to the heat sink base and fins, the piezoelectric fin heat

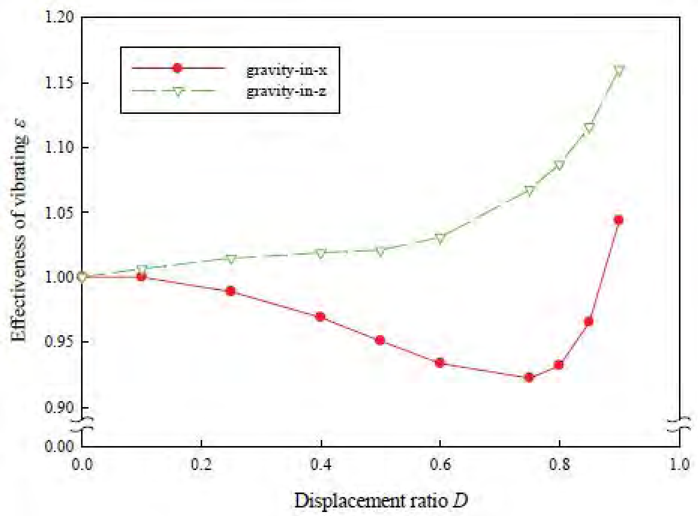

Figure 10. The Effect of Gravity Direction [1]

sink always outperforms the traditional heat sink. The idea of integrating piezoelectric fins in a heat sink is novel and looks promising in LED cooling applications. However, the study of Ma et al. [1] shows that the effect of vibrating fins on enhancing the convective cooling is not straightforward. In a bad configuration, the vibrating fins may hamper the cooling of the heat sink. To prove the benefits of the piezoelectric fins, further study and tests are needed to validate the potential of the concept. Also, there are some practical issues that need to be investigated prior to the use of the piezoelectric fins, such as the fin stress and reliability under large vibrating amplitude, the noise level of the vibrating fins at higher frequencies and the life expectancy of the piezoelectric material, etc.

Reference:

1. Ma, H. K., Chen, B. R., Lan, H. W., and Chao, C. Y., "Study of an LED Device with Vibrating Piezoelectric Fins" Semiconductor Thermal Measurement and Management Symposium, SEMI-THERM 2009, 25th Annual IEEE.